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The documentation of archaeoacoustics identity of Sultan-Barquq complex

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Abstract Sultan-Barquq complex is considered to be the most compact and unified Islamic Mamluk monuments in Cairo. In addition to its main function as a place of prayer, its design allows separate schools for teaching the four Sunni rites. Both functions are concerned with the importance of acoustical perception and intelligibility of speech, as the most important characteristic of the archaeoacoustics identity of the worship spaces. This study aims to obtain documentation for the acoustical identification (ID) of the mausoleum at Sultan-Barquq Complex. The acoustical ID explains the acoustic features in relation to form and texture. By comparing the criteria of good acoustics with spatial requirements and design guidelines, the scientific interpretation could be obtained. The acoustical environment within Sultan-Barquq mausoleum has been investigated and examined through field measurements and room simulations using Odeon. Measurements showed a high reverberation time and echoes at some of the examined points. The interpretations of these measurements give the features of the archaeoacoustics identity (acoustical ID) of Sultan-Barquq mausoleum.

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1. Introduction

The Archaeoacoustics in archaeological buildings is of great interest. However, no intensive work was done to obtain a clear documentary image of archaeoacoustics identity of the Islamic era, despite its longevity and importance in Egypt.

Archaeoacoustics Identity for worship spaces is considered a way to learn about the history of civilizations. Among these places are mosques. The acoustics within any space in it are determined by the characteristics of that space. Of primary interest here is the acoustical communication channel between minber (pulpit) or Qur'an reciter and prayer hall in spaces of mosques (see Figs. 1 and 2).

Archaeoacoustic Identity for Mosques is an approach based on field - recording, artistic audio–video documentation from the output of space users and those who maintain it. Whereas the research of the unique acoustic definition representing that culture. Hence, it can be defined that the

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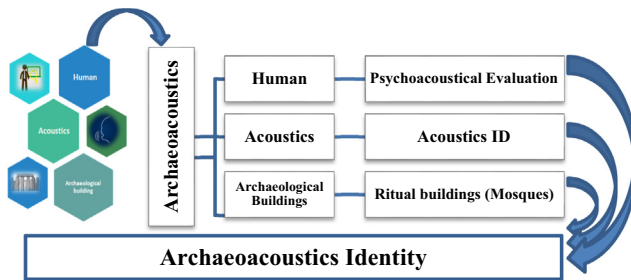


Fig. 1 Diagram illustrates archaeoacoustics definition which is about putting acoustics findings (acoustical ID) of archaeological building (mosque) in human context to be useful in documentation of archaeoacoustics identity. Source: The Authors.

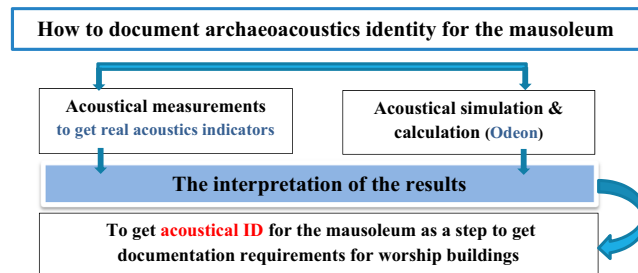


Fig. 2 Diagram showing how to document archaeoacoustics identity for the mausoleum. Source: The Authors.

acoustical Identity for the archaeological mosques as the consistent development of a unique acoustic for archaeological worship buildings. Along the lines of the visual identity, the acoustic elements are derived from the building values and the building geometry. To achieve the objective, which is creating a consistent identity with a strong recognition value to the archaeological mosque, Acoustical ID must be found [4].

Acoustical ID expresses the intelligibility of both speech and other sounds, especially for holy tones that must be both spacious and effective. As shown in Fig. 3 the Archaeoacoustics ID (Acoustical ID) is divided into two parts, each of which affects the other. The first part contains the visible physical features of the mosque, such as (the geometry of the mosque,

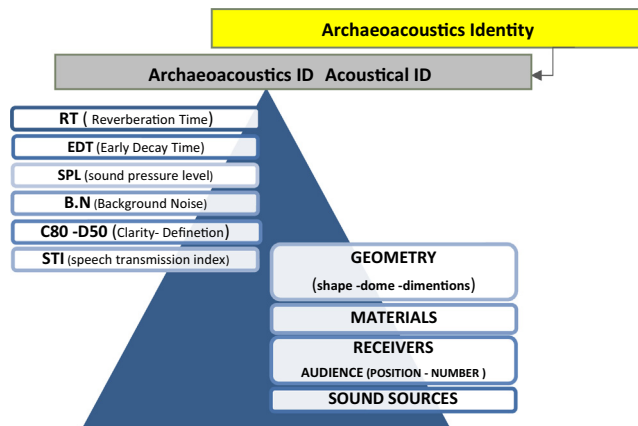


Fig. 3 Diagram showing the definition of Archaeoacoustics ID. Source: The Authors.

the finishing materials and the position of sound source and receivers). The second part contains the indicators that affect the acoustical performance inside the mosque such as reverberation time (RT), speech transmission index (STI), sound pressure level (SPL), Early Decay Time (EDT), Background noise (B.N), Clarity (C_{50}) and Definition (D_{50}). The indicators were chosen based on multiple studies which investigate the impact of some mosques geometry on the archaeoacoustic identity to achieve the desired intelligibility of speech [3,5,15] (see Fig. 4).

The main objective of this work is to add a new dimension to the documentation of the acoustical Identity of sultan-barquq mausoleum, and find out whether architects who built such huge building have considered the acoustics problems in their designs or not. With the aim of assisting the conservation officials to restore the acoustic formation of the original case on which the complex was built.

Sultan Barquq complex is a unique piece of Islamic architecture in historical Cairo and can be considered a comprehensive religious university in accordance with contemporary learning concepts. Despite the importance of the mosque in terms of history, archeology, architectural and historical grandeur, it has not received the attention it deserves. This building was not the subject of acoustical research despite the importance of the acoustical role in such spatially close spaces with its different functions. There were two steps to find out whether the worshipers hear and understand clearly the words of the Qur'an reciters or not. Firstly, reconstructing the acoustic environment within the Mausoleum as originally (by Odeon), and then evaluating the acoustical environment through the seven measured acoustical indicators: (RT), (EDT), (SPL), (B.N), (C_{50}), (D_{50}), (STI). This was done paral-

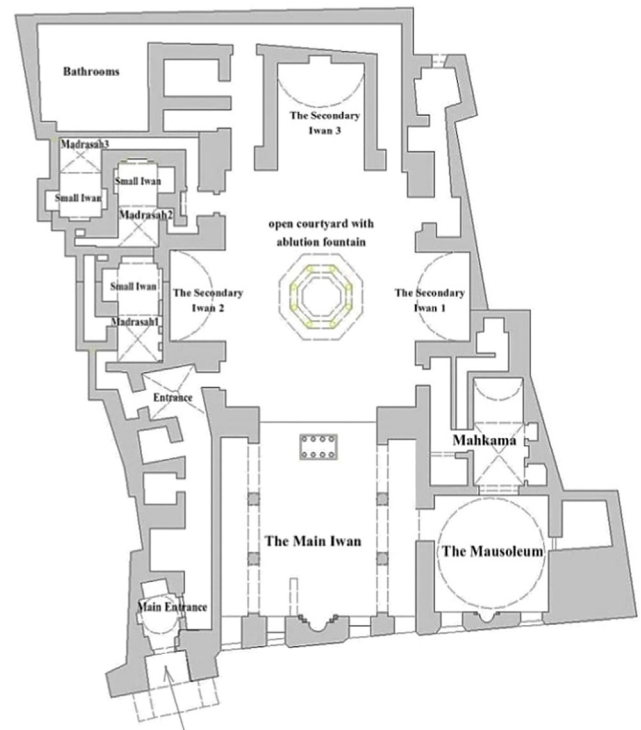


Fig. 4 The plan of sultan Barquq complex. Source: The Authors.

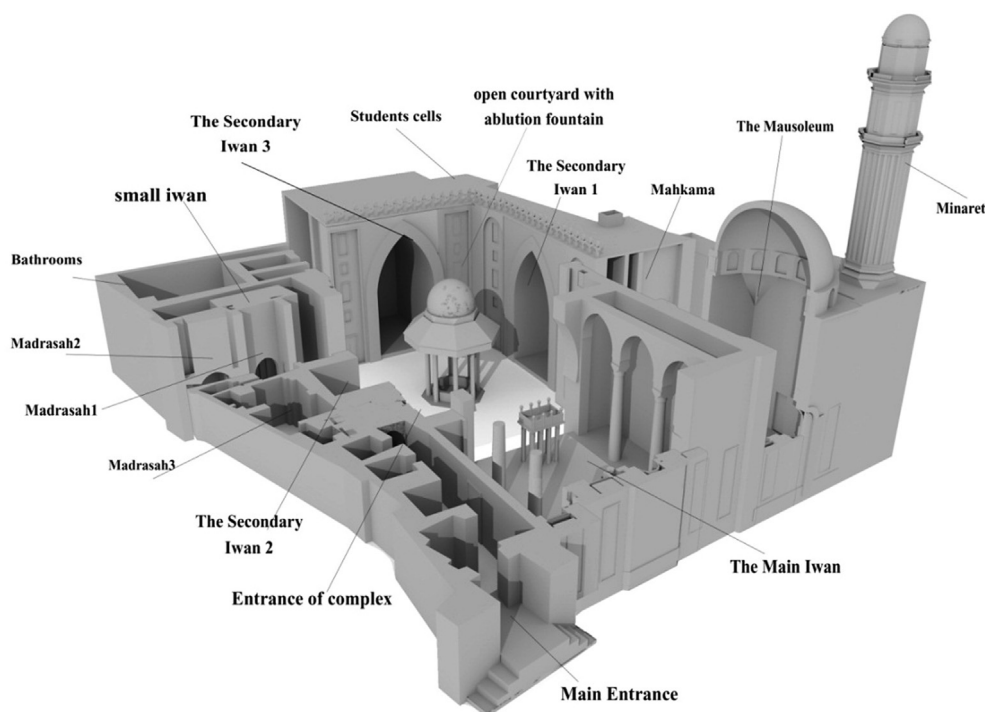


Fig. 5 3D representation of the main items that compose sultan barquq complex. Source: The Authors.

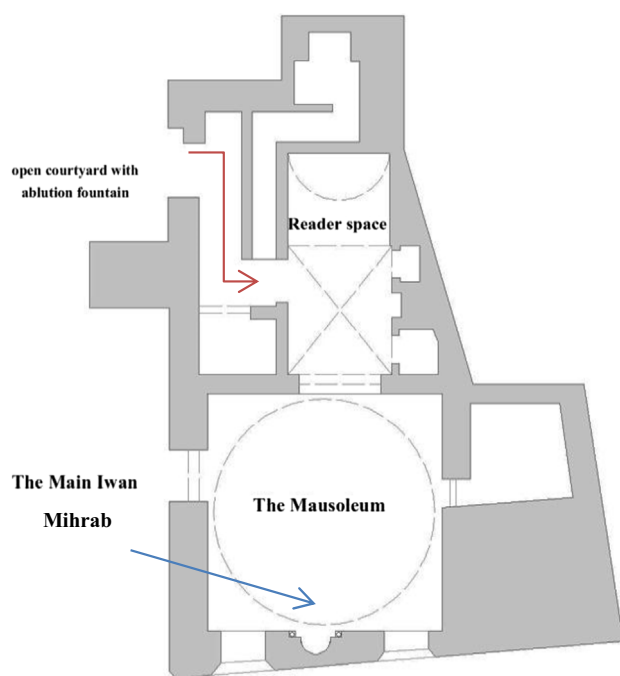


Fig. 6 Shows the mausoleum plan. Source: The Authors.

rel to the field measurements and would be documented in the form of Acoustical ID.

2. Description of sultan barquq Complex:

Sultan Barquq complex, like most Mamluk foundations, served several functions at a time. The foundation deed states

that the complex includes, in area (80×50) m², a Friday mosque, a madrasa that taught the four Sunni mazhabs, a khanqah and a mausoleum whose dome is visible from the street [2].

- A central open courtyard surrounded by four Iwans which are halls without intermediate columns, usually open on one side to a courtyard and raised one step from the courtyard level and has a rectangular shape of area (21.70×17.75) m².
- The main Iwan, also known as the Qibla (the direction to the Holy Ka'aba) Iwan. It has a rectangular shape of area (17.60×14.70) 260 m² and three small Iwans surround the central open courtyard; each of the northern and southern Iwans consisted of rectangular areas of about (5×7.75) m²; the Western Iwan has a rectangular shape of area (9.10×7.75) m². Each Iwan is covered by a pointed vault that has the same height.
- Barquq Madrasas (schools) includes an old huge building formed out of huge rocks. The old building is meant for the accommodation of over 100 students and teachers. Each Madrasa consists of a small open Iwan.
- Adjoining the prayer hall on its northern side, there is a mausoleum chamber under the dome, but separated by a wall.

3. The mausoleum as a case study

The mausoleum is located underneath one of the four iwans to the north side of the prayer hall. It is found directly after a decorative passage that leads into the mausoleum. The dome above the mausoleum has wooden pendentives that are painted with magnificent decorations. The windows of the mausoleum are of shiny colorful glass that radiates the sun

light all day long. During the nineteenth century, the Arabic Antiquities Preservation Committee meritorious work in renovating buildings Architecture Group, overhauled its marbles and its carpentry and right buildings repaired roofs wezehbtha, the big dome also created years 1311 e/1893 m according to an old picture and kept the old colored decorations and gilt.

3.1. The geometry of the mausoleum

The next part explores the most significant sound diffusion and amplifying elements. This had been prominently introduced to historic religious architecture which forms the acoustics identity of the Mausoleum, i.e. the dome, the Mihrab and the muqarnas.

3.1.1. Architectural and statistical data

See Table 1.

3.1.2. The dome & Mihrab & Muqarnas of the mausoleum

The Dome is classified as a central dome because it mediates the ceiling of the square Mausoleum (Fig. 7). It also classified as a hemispherical dome because there is one half of a sphere, constructed on a circular ring beam that contains The windows of the mausoleum. The dome of the ceiling height is 7 m, but its height 20 m from the ground. The dome itself was originally made of wood but was reconstructed in smooth brickwork and covered with smooth limestone constructed on a circular ring beam that covered with decorated wood, by the Comité in 1893 [7,8] (see Figs. 8–12).

The Mihrab wall and the qibla also have a marble decoration that closely resembles the qibla wall in the prayer hall, but the Mihrab here is noticeably narrower. The Mihrab may have been designed in this way to allow the surrounding windows to be wide enough for the Qur'an reciters to sit, as they could be heard by those passing on the street outside. Architecture of the Mihrab has always been one of the main features of mosque architecture.

The Mausoleum Mihrab is classified as tulunid Mihrab. The Mihrab covered with a panel of marble fixed together as a part of marbled qibla wall [9].

The Muqarnas is a structural and decorative architectural component that may appear in different designs and shapes,

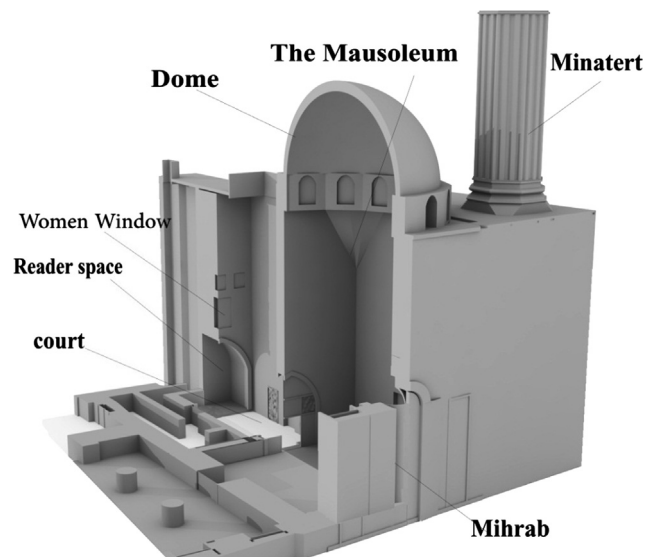


Fig. 7 The details of mausoleum of sultan barquq complex. Source: The Authors.

composed of different layers of elements called tiers. The cells look like small pieces of a vault while intermediate elements can be used to combine cells. The Muqarnas act as the transition between the rounded dome above the square Mausoleum below that accomplished by the original wooden pendentives (though restored). The Muqarnas gilded décor was made with similar quality to that on the ceiling of the prayer hall. There are four wooden muqarnas in the four corners of the mausoleum. The Muqarnas is classified as pole table muqarnas because the center of the pole and the star shaped elements [10].

3.1.3. The sound sources & receivers in the mausoleum

There are two sound sources in the mausoleum:

- The first sound source in the funeral service case is one human sound source; the prayer, facing in the opposite direction to the audiences and sitting in the Mihrab.

Table 1 Architectural and statistical data of the mausoleum, Source: The Authors.

Dimensions		L	W	H	Area	Volume
	Mausoleum	10.32 m	10.23 m	20.6 m	106 m ²	2175 m ³
	Qur'an reciter	4.50 m	3.93 m	4.85 m	17.70 m ²	86 m ³
	court	5.55 m	4.58 m	16 m	25.5 m ²	407 m ³
Finishing Materials	Ceiling	The Qibla		The Side		Floor
	-Central Dome, −4 Muqarnas of Wood decorated	Lower: 8.5 mMarble cladding Upper: stone		Lower: 7 m Marble cladding Upper: 2 m stone		Marble
Statistical Data	Max. Capacity Persons	Area/ Person m ²	Volume / Person m ³		Environmental Conditions	
	50	0.7	16		RH % 22	Temp. C° 25.4



Fig. 8 The dome of the mausoleum. Source: The Authors.

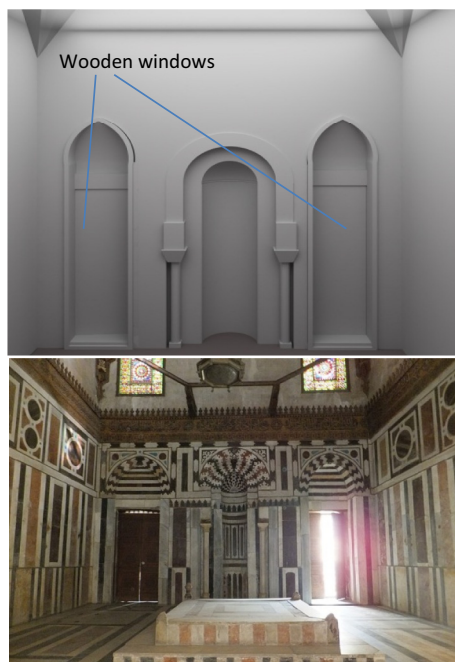


Fig. 9 The Mihrab wall of the mausoleum of sultan barquq complex. Source: The Authors.

- The second sound source of Qur'an reciter in the reader space outside the mausoleum.

The receivers (prayers) are standing around the mausoleum, the receivers height is 1.6 m.



Fig. 10 The Muqarnas of the mausoleum. Source: The Authors.

3.1.4. The effect of dome & Mihrab & Muqarnas acoustically

We can analyze the effect of the geometry elements, that forms the mausoleum space, on the acoustic performance, which in turn constitutes the acoustical identity of the mausoleum. There are two distinct acoustical requirements for the prayers in the mausoleum; to hear Qur'an reciter in front of the Mihrab or in the reader space outside the mausoleum Fig. 6. These requirements need to achieve intelligibility of speech and a high sound quality for musical of the holy koran. Therefore, some acoustical indicators such as reverberation time (RT), speech transmission index (STI), sound pressure level (SPL), Early Decay Time (EDT), Background noise (B.N), Clarity (C_{50}) and Definition (D_{50}) will be measured by simulation (Odeon) in parallel with field measurements to be documented in an acoustical ID form of the mausoleum [6].

The form of the investigation involved the construction and analysis of a 3-D model using the acoustic simulation program ODEON in parallel with field measurements. Fig. 5 shows external and internal views of the ODEON model. The measurements of reverberation time in the tested space under consideration were carried out according to ISO 3382 [15]. Hand-held Analyzer Type 2270 (B&K) was used with connection of condenser microphone type 4189 (B&K) and omni directional loudspeaker type 4292 (B&K) with power amplifier 2716 (B&K). Using the Building Acoustics Software BZ-7226, the analyzer generates noise test signal and excites the reverberation room through third octave filtered noise signal. The reverberation time measured in different points through the studios.

3.2. Results and discussion

To obtain conclusions regarding the acoustic performance in the mausoleum, seven objective acoustic indicators have been analyzed. According to their importance; these indicators are:

3.2.1. The reverberation time (RT)

The reverberation time is the time takes for a room to reduce the sound power by 60 dB. This parameter is very important and is used as a baseline for designing a room that is prepared for either speech or music. In practice, the evaluation is limited to a smaller interval of the decay curve, from -5 dB to -35 dB, (T_{30}) below the start value; but still relating to 60 dB decay.

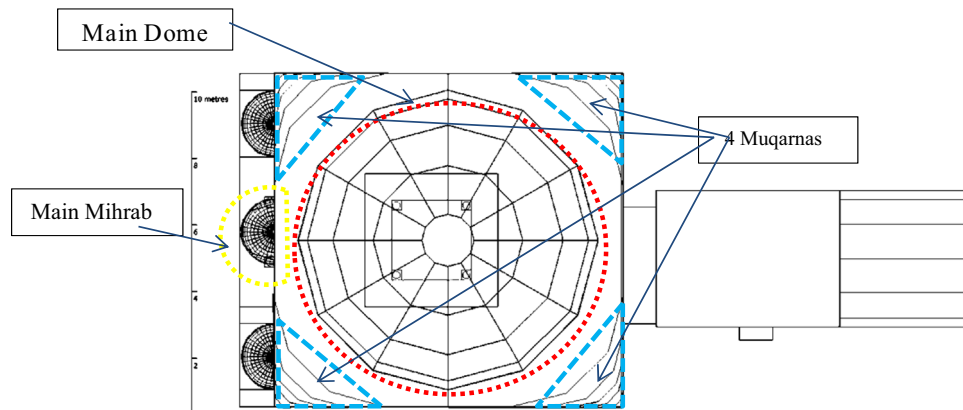


Fig. 11 The ODEON Model, external view. Of the mausoleum of sultan barquq complex. Source: The Authors.

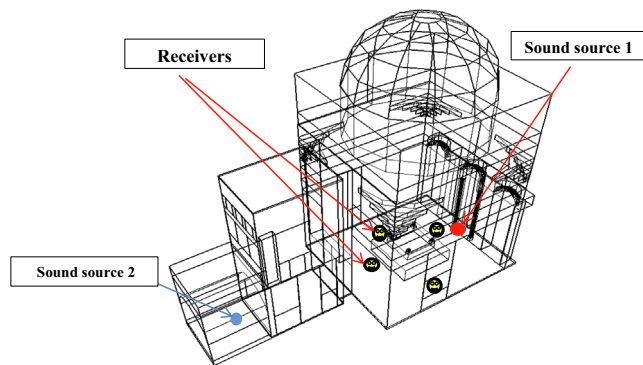


Fig. 12 The ODEON Model, internal view of the mausoleum of sultan barquq complex. Source: The Authors.

There are no optimum values for RTs of the mosques in the literature. Fig. 13 shows a grid of measurement points, p1, p2, p3, p4. As for the reverberation time (RT) obtained for octave band frequency between 63 Hz and 8000 Hz, the value between 500 Hz and 8000 Hz is chosen as the optimum value.

as shown in Fig. 14 - the first case (sound source 1)- the values of measured average reverberation time RT (T_{30}) range between 3.49 sec at 500 Hz to 1.24 sec at 8 KHz for the unoccupied field case and between 2.70 sec at 500 Hz to 0.92 sec at 8 KHz for the unoccupied simulation case [11].

Excessive RT was not unexpected due to the nature of the geometry of the mausoleum such as the high height, the diameter of the dome of the mausoleum 9.80 m, that leads to a more dispersed distribution of the sound reflections of the dome, the marble walls and floors, the absence of carpets, and the weak absorption ratio represented by the four wooden Muqarnas.

as shown in Fig. 15- the first case (sound source 1)- the values of measured average reverberation time RT range between 3.49 sec at 500 Hz to 1.24 sec at 8 KHz for the unoccupied field case. But in the second case (sound source 2) the values of measured average reverberation time RT range between 3.97 sec at 500 Hz to 1.66 sec at 8 KHz for the unoccupied field case. When changing the source of the sound in the second case, where the location of the qur'an reciter outside the mausoleum, the range of RT (T_{30}) became low because of

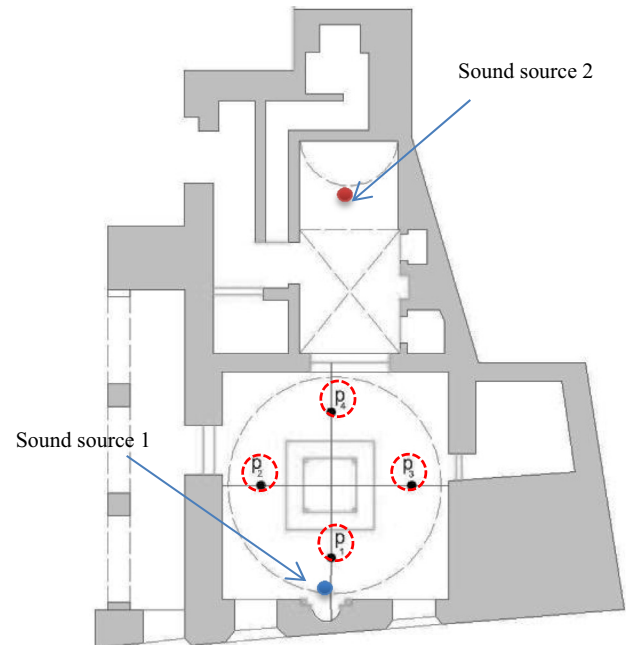


Fig. 13 Measurement points in the mausoleum. Source: The Authors.

the separator open courtyard and the distance from the receivers (see Fig. 16).

The values of T_{30} decrease in high frequency range the low values at high frequency are mostly caused by used sound absorbing materials in the mausoleum such as the wooden Muqarnas and cylinder round beam [12].

Because of the inaccuracy 3-D model using the acoustic simulation program ODEON for some complex geometrical elements within the mausoleum space such as Muqarnas. Therefore its effect was studied separately, to get accurate results of acoustics for sultan barquq mausoleum. So we can study the effect of the mausoleum four Muqarnas of sultan barquq complex by comparing RT (T_{30}) in three cases:

- Case 1: Four Muqarnases in the mausoleum.
- Case 2: Only two Muqarnases in the mausoleum.
- Case 3: No Muqarnases in the mausoleum.

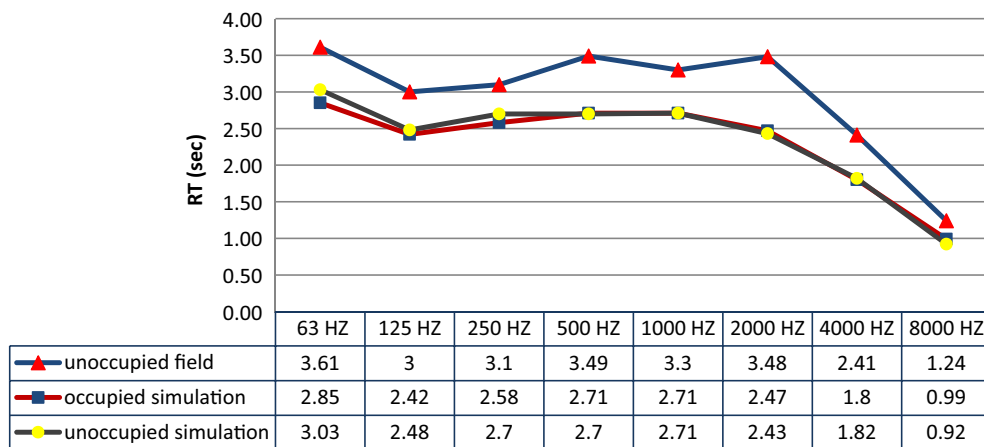


Fig. 14 Measured T30 values of the receiver points in the mausoleum. Source: The Authors.

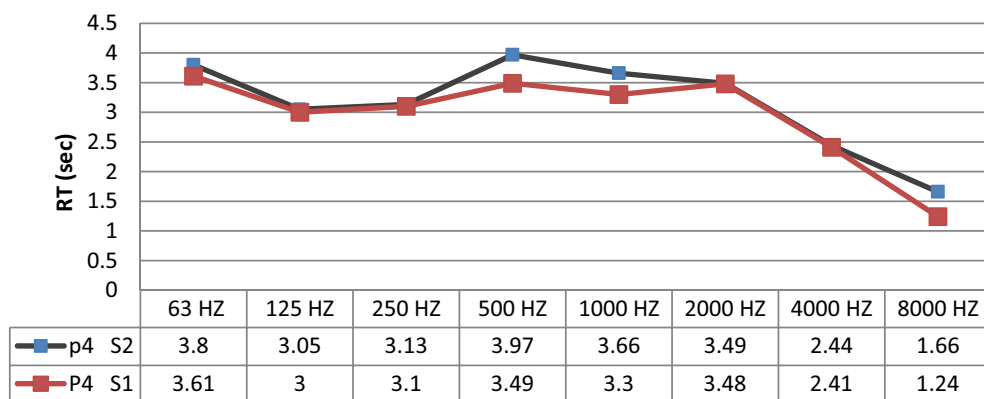


Fig. 15 Measured T30 values of the receiver point p4 of case 1&2 in the mausoleum. Source: The Authors.

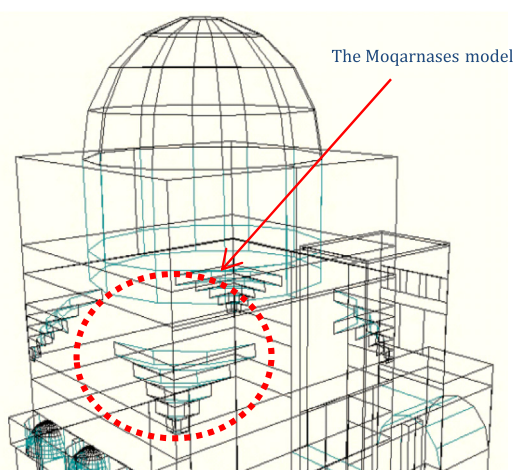


Fig. 16 The Odeon model of the four Muqarnas.

Muqarnas's role is summarized that its contains a surface irregularities and scattering elements to treatment sound with solid surfaces, either with irregular surfaces that break up and scatter sound waves in multiple directions, or convex curved surfaces to divide the frequencies gently and diverge in multiple directions. As a result, the Muqarnas enhance the

hearing state within the room. The Muqarnas made of wood that absorb a part of the sound of the incident. Instead of removing any sound energy, this will cause high-quality sound throughout the room [13].

As shown in Fig. 18 the values of T30 that inferred from the simulated results Fig. 17 based on the field measured values Fig. 14 increase by percentage expressed by factor (F) ranges from 1 to 1.3 along the octave band frequency between 63 Hz and 8000 Hz (see Figs. 19–22).

The values at 500 Hz is chosen as the optimum value. As shown in Fig. 18 in the case of the four Muqarnas, the value of the T_{30} range between 3.49 sec, While the absence of two Muqarnas the value of the T_{30} range between 3.68 sec, Either in the absence of the four Muqarnas the value of the T_{30} range between 3.91 sec. The results means that the value of T_{30} increases in the absence of Muqarnas on average 0.21 sec and it is an insignificant, negligible rate for increasing the reflective surfaces of the mausoleum space.

3.2.2. Early decay time (EDT)

Early Decay Time has to do with the first sound reflections only. If a sound source is continuous, e.g. speech or music, a lot of the reverberation of a sound incident will be masked by the next sound incidents. Thereby the late part of the reverberation will become unnoticeable. Early decay time has to do with the first –10 dB. Since the early part of the decay is dom-

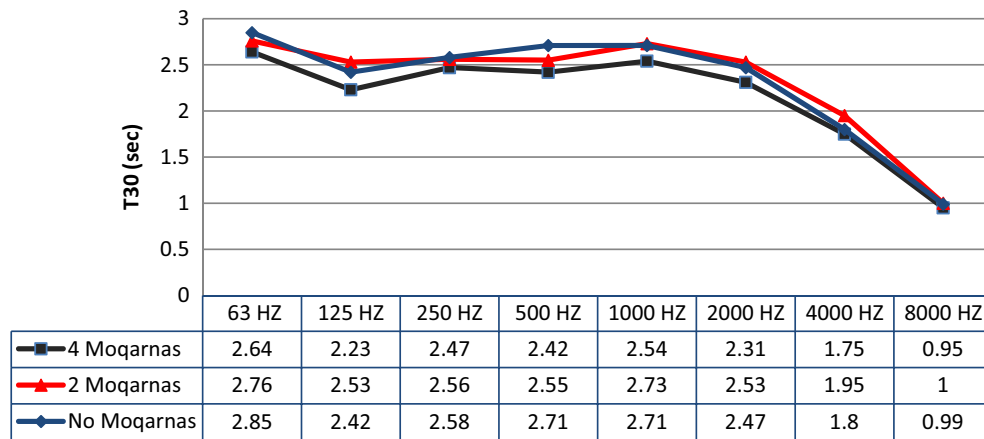


Fig. 17 Simulated T30 values of the receiver point in the three cases of the mausoleum Muqarnas. Source: The Authors.

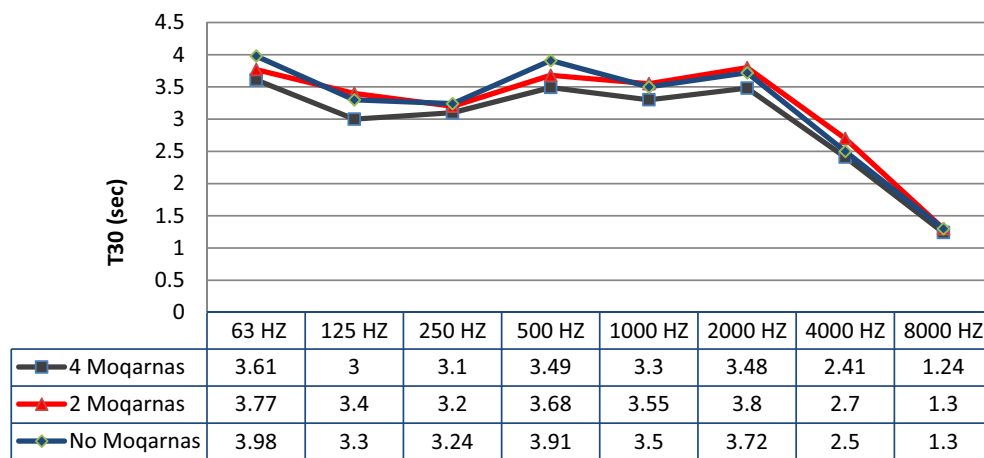


Fig. 18 Inferred real T30 values of the receiver point in the three cases of the mausoleum Muqarnas. Source: The Authors.

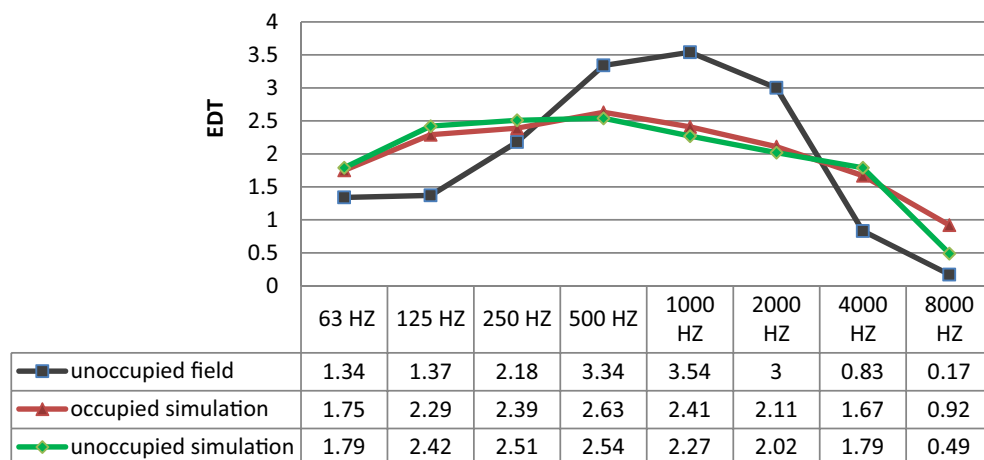


Fig. 19 Measured EDT values of the receiver point of the mausoleum. Source: The Authors.

inated by the direct sound and it is much steeper than the rest, EDT is usually shorter than the rest type of reverberation times. The Relative similarity for inclination of the T30 and

EDT graphs shows the uniform distribution of the sound within the room. We can get the optimum value by the equation $RT - (\%10 \times RT) \leq EDT \leq RT + (\%10 \times RT)$.

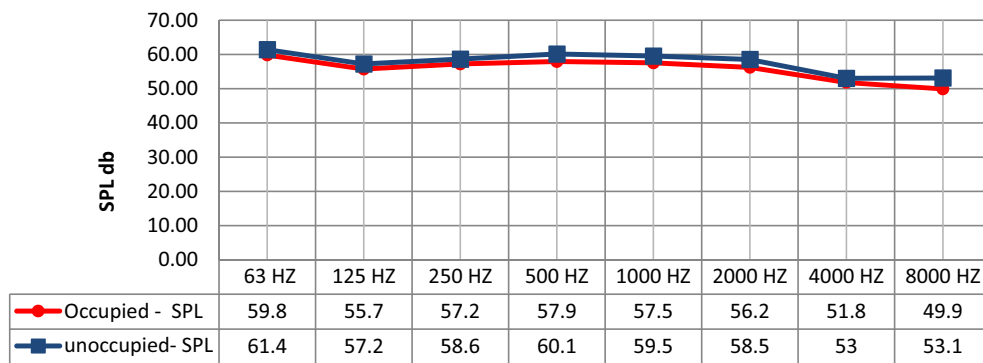


Fig. 20 Measured SPL values of the receiver point of the mausoleum. Source: The Authors.

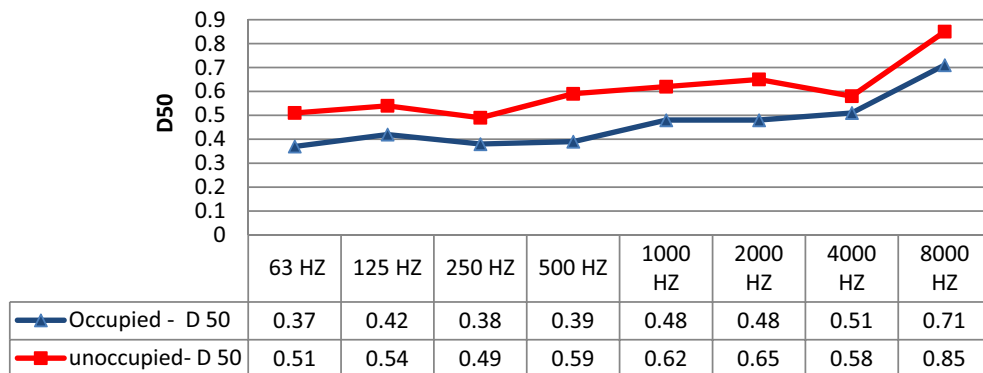


Fig. 21 Measured D50 values of the receiver point of the mausoleum. Source: The Authors.

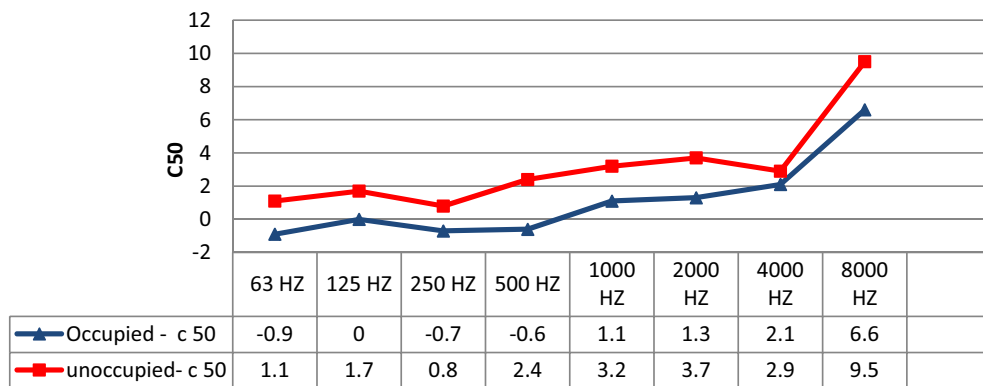


Fig. 22 Measured C50 values of the receiver point of the mausoleum. Source: The Authors.

3.2.3. Background noise (B.N):

The mausoleum obtained value of 35–40 based on the calculation of the presence of background noise inside the mausoleum when windows opened. In some cases, Due to the absence of important activities around the mosques and the absence of mechanical and electronic devices active inside it, where the sound criteria level corresponding to religious buildings is between 25 and 30, so the level of noise was practically negligible.

3.2.4. Sound pressure level (SPL)

SPL is the result of variations in air pressure achieved by sound waves. The lowest pressure is called a sound that can be heard by the human is called the hearing threshold. The

highest level is known as pain threshold. The average sound for human (speech) SPL is 50–70 Db.

We can observe that the sound pressure level values decrease with the distance from the sound source. The maximum values are located at the areas near the Mihrab and at the two sides. In general, this case has a noticeable increase of SPL value at the most critical point, which is behind the sound source. Both measurements and simulation data indicate that the SPL values range from 57 to 60 dB at the important speech frequencies.

3.2.5. Definition (D50) (%)

D50 is mostly regarded as a parameter related with speech, and higher values are expected for better intelligibility. the struc-

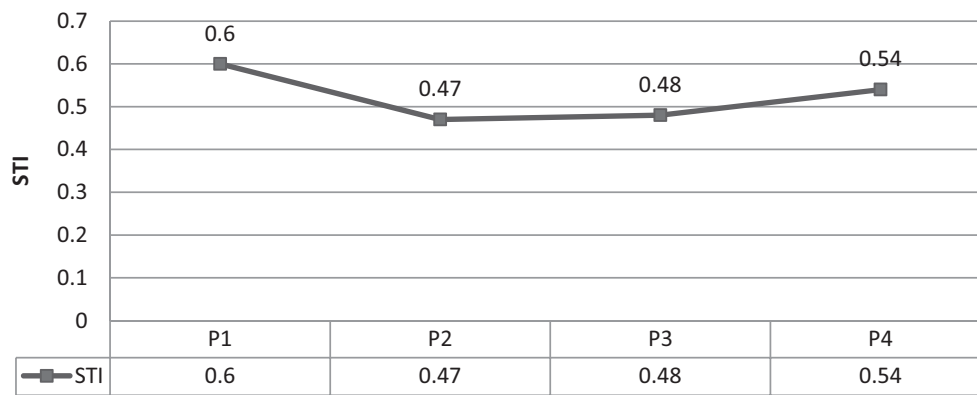


Fig. 23 Measured STI values of the receiver point of the mausoleum. Source: The Authors.

ture of a higher dome produces better intelligibility and clarity speech as it has been indicated by the increasing of C50 parameter, optimal range $0.50 < D50$

3.2.6. Clarity of speech (C50) (dB)

Another measuring tool of intelligibility is C50. Here the ratio of energy before and after 50 ms in decibels is measured. The integration of sound arrivals within 50msec with direct sound is due to the human nature of our ears. Values above the zero line depict more energy arrivals before the 50msec than after it what enhances the direct sound and increases clarity.

3.2.7. Speech transmission index (STI)

Speech Transmission Index has also been investigated since it is one of the most popular parameters to evaluate the intelligibility. Fig. 23 shows that the STI values indicate the clarity of good speech about 54–60%, which means good clarity according to the STI classification shown at the right table, so STI values is fair at some points and good at other [14].

4. Conclusion

This work represents a documentation and analysis of the acoustic characteristics of the mausoleum in Sultan Barquq complex. The acoustical environment was examined and studied the effect of the mausoleum basic geometry (dome, Mihrab and Muqarnas) on the acoustics indicators. That examination was done via field- measurements and simulation of the mausoleum utilizing Odeon. Therefore, we could assess the degree of clarity resulting from that effect. The field measurements were utilized to validate Odeon outputs. Considering the inaccuracy simulation of some complex geometrical elements within the mausoleum space such as Muqarnas, therefore, its effect was studied separately to achieve more accurate results. These results are shown in the following:

- The values of T_{30} that were inferred from the simulation were increased by percentage expressed by factor (F) ranges from 1 to 1.3 along the octave band frequency between 63 Hz and 8000 Hz.
- The value of T_{30} was increased in the absence of Muqarnas on average 0.21 sec. this value was insignificant, having

negligible rate for increasing the reflective surfaces of the mausoleum space.

The evaluation of the results was made on the criteria of good acoustics of worship buildings with the spatial requirements of the mausoleum space. The field measurements overestimated in some acoustical values for the examined points. Whereas, the values of measured average reverberation time RT (T_{30}) achieve 3.49 sec at 500 Hz for the unoccupied field case.

Excessive RT was expected due to the nature of the geometry of the mausoleum. Upon changing the sound source (the qur'an reciter) location outside the mausoleum, the range of RT (T_{30}) became low because of the separator open courtyard and the distance from the receivers.

The change of T_{30} affects all other indicators of acoustics; the relative similarity for inclination of the T_{30} , EDT and SPL graphs shows the uniform distribution of the sound within the mausoleum, the increasing of D_{50} to 0.85 and C_{50} values to above the zero line, indicate intelligibility and clarity of speech. Also, the STI values indicate the clarity of good speech in a range of 54–60%.

The overestimation of the indicators values is due to two reasons:

- In the Mamluk era in which the mausoleum was built, the proportion of absorbed surfaces was sufficient to reduce these echoes. Such as the presence of carpets on the entire surface of the mausoleum floor, as in the Sultan Hassan Mosque, but the measurements were made on the current status of the mausoleum as there is marble floor that could increase the echoes.
- The sacred background for worship spaces, especially the mausoleums, was aimed at deliberate overestimation in the acoustical performance to control the spiritual case of the worshiper inside the mausoleum. This also was applied for the audiences outside with evidence of existence large windows on the sides of the Mihrab that were opened to listen to audiences outside the mausoleum.

This analysis adds a new dimension to the documentation of sultan-barquq complex, which is the acoustics identity. This was done through acoustical documentation to restore its Acoustic Formation achieving the original case on which the complex was built.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Further reading

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